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[illegible] OF EXPERIMENTS CONDUCTED IN THE HIGH-PRESSURE SHOCK TUBE
OF THE GAS DYNAMICS LABORATORY AT NASA

Proposed Talk for Third Shock Tube Symposium
March 10-11, 1959
Hotel Chamberlin, Old Point Comfort, Va.

By Jim J. Jones

This talk describes several investigations performed at the gas dynamics laboratory of the Langley Research Center, NASA. Most of the experiments described were conducted in the gas dynamics high-pressure shock tube. It is a constant-area tube, 3-3/4 inches in diameter. The high-pressure chamber is 14 feet long and the low-pressure chamber has a working length of about 70 feet, although at the time that attenuation was studied it was considerably longer.

Shock-Wave Attenuation

Shock-wave attenuation has been studied in this tube for some time, largely from the standpoint of shock-tube technology rather than the basic flow physics. That is, what are practical drivers to use to produce the desired shock strengths; what is the relative shock attenuation for each driver, and, what is the resultant flow behind the shock wave like?

Those drivers which have been investigated are helium, hydrogen, constant-volume combustion of H_2 and O_2, diluted with helium and a constant pressure combustion of a similar mixture. In all cases, air was the driven gas. Some consideration was also given to a double diaphragm or three-chamber arrangement.

The first slide summarizes the attenuation rate for these various drivers. The low pressure p_1 was the same for each run. Notice that, except for the helium driver, each of the runs has about the same shock Mach number at about 225 diameters. Very high helium pressure would be

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required to generate a shock wave of the same strength at 225 diameters as the others shown, so a weaker shock is presented for comparison.

The constant-volume and constant-pressure combustion drivers were identical except for the strength of the diaphragm used. Constant-pressure drivers have been shown by Hertzberg and others to have rather poor reproducibility.

Hydrogen-rich mixtures, that is, mixtures of, say 8 percent or 10 percent O_2 and the balance of H_2, have been attempted but the tendency of the combustion to become a detonation has caused us to abandon this type driver.

The difference in shock-wave attenuation is quite marked for the various drivers and follows the general rule that the more efficient drivers in producing strong shock waves display the higher attenuation rates.

Measurements of the time history of the static pressure immediately behind the primary shock also show characteristics associated with each particular driver. (See slide 2.) These pressure records were all made some 200 diameters from the diaphragm and are therefore influenced by the very sizeable amount of attenuation which the shock has undergone. Pressure level and shock strength influence the pressure history, of course, but comparisons show that, in general, cold gas drivers, hydrogen and helium, show a short period of nearly constant pressure and then a rising pressure. One can see, for example, that for the helium driver case shown, the pressure has about doubled in the first millisecond.

The higher attenuation rate of the combustion driven shocks indicated that stronger downstream expansion waves are overtaking the shock. These expansion waves are present largely because of the cooling of the hot combustion gases. The effect of this increased strength of the expansion waves is to cancel the tendency of the pressure to increase with time. Thus, as illustrated in slide 3, combustion-driven shock waves show a nearly constant pressure and in some cases a decrease in pressure. This is not to infer that other flow properties are constant with time. For example, it can be inferred that the stagnation enthalpy increases rapidly with time. Another rule seems to exist here: the more efficient drivers, although posessing higher attenuation rates, show a more constant-pressure history in the driven gas.

The gas dynamics laboratory has one rather small three-chamber shock tube. It is described in more detail by Mr. Evans in his talk. The driver and buffer chambers are four-inch diameter and the low-pressure chamber is one-inch diameter. Hydrogen-helium air and helium-helium air combinations are used in this tube. The maximum shock strengths attained are compared with the theoretical values in slide 4. In all cases the middle, or buffer gas, was adjusted to its theoretical optimum pressure for the particular over-all pressure ratio. It may be seen that agreement with theory is somewhat better for the helium driver than for the hydrogen driver. A single diaphragm, H_2-air curve for a constant-area tube is presented for comparison. Two effects account for the superiority of the three-chamber configuration curves - the area change and the addition of the buffer gas. This figure does not show the relative importance of each. The shock attenuation rate approximation is the same in the three-chamber tube as in the 3-3/4 inch tube for like drivers. This work has been reported by Mr. C. J. Schexnayder in the August issue of the Journal of Aeronautical Science.

The three-chamber shock tube just discussed has an area reduction by a factor of 16 at the second diaphragm. The effect of this area change on maximum attainable shock strengths has been recognized. It becomes important, however, from another viewpoint as well. Most theoretical discussions neglect the attenuation in the buffer chamber. It is not, in the general case, negligible as may be seen in the next slide (5). A few runs made in the constant 3-3/4 inch diameter tube with a three-chamber arrangement showed that the attenuation in the center chamber cancelled the beneficial effects of the double-diaphragm configuration. The driver was constant-volume combustion and the buffer gas was helium. The attenuation of the shock wave from M_s = 3-1/4 to $M_s = 2.4$ lowered the maximum shock strength in the air from a theoretical M_s = 9-1/4 to an experimental value just over 7. This indicates the importance of maximizing the buffer chamber diameter.

Heat Transfer

An investigation has been made of flat-plate heat transfer for a range of Reynolds numbers from 10^4 to over 10^7. The model configurations used are shown in slide 6. The surfaces to which the heat-transfer rate was measured were pyrex. Hanovia paste resistance thermometers were used to measure the surface temperature. A wedge was used for the lower Reynolds number range. It was necessary to have a steel leading edge on the wedge to avoid chipping so there was a steel-to-glass joint ahead of the measuring stations.

In order to obtain a long run of boundary layer with a minimum of interference effects, a hollow cylinder was utilized. Again a steel leading edge was necessary. The cylinder was 50 millimeters pyrex tubing, 24 inches long.

An estimation of the boundary-layer-displacement thickness at the trailing edge of the cylinder indicated that it was 4 percent or less of the radius of the cylinder. The slight pressure gradient induced by the area change has been neglected in reducing the data.

Slide 7 shows the data obtained for a range of shock Mach numbers from 4.6 to 10.5. The wedge data is based on conditions behind the oblique shock wave.

The data correlates quite well with the incompressible relations if the heat-transfer parameter is based on stagnation-to-wall enthalpy difference. Rose, Probstein and Adams have proposed this relation for the turbulent case.

These data, although obtained at high static temperature and low stream Mach number, as is typical of all data obtained in a constant-area shock tube, can be shown to be directly applicable to hypersonic flight in the atmosphere. If one considers the case of a wedge, or compression surfaces, with a blunt leading edge, the conditions just outside the boundary layer some distance from the leading edge are very similar to the conditions of the present data. As an example, one run of the present data was selected ($M_s = 8.45$) and it was found that the stream and stagnation conditions matched those on a blunted 8^o half-angle wedge flying at $M = 13.5$ at 70,000 feet.

Probe Electrification

A phenomenon of some interest which appears in shock-tube investigations is the charge acquired by any probe placed in the flow.

Early efforts to obtain heat-transfer data in the shock tube with an evaporated thermocouple indicated that "hash" or extraneous signal predominated over the thermocouple signal for cases in which the shock Mach number was about 6 or greater. The hash could be reduced but not eliminated by balancing the resistance to ground of the two thermocouple leads. The trouble could be eliminated in a resistance thermometer by shunting across the thermometer and centertapping the shunt to ground. It was not possible to do this in the case of a thermocouple, of course, since the thermocouple requires a high-resistance circuit.

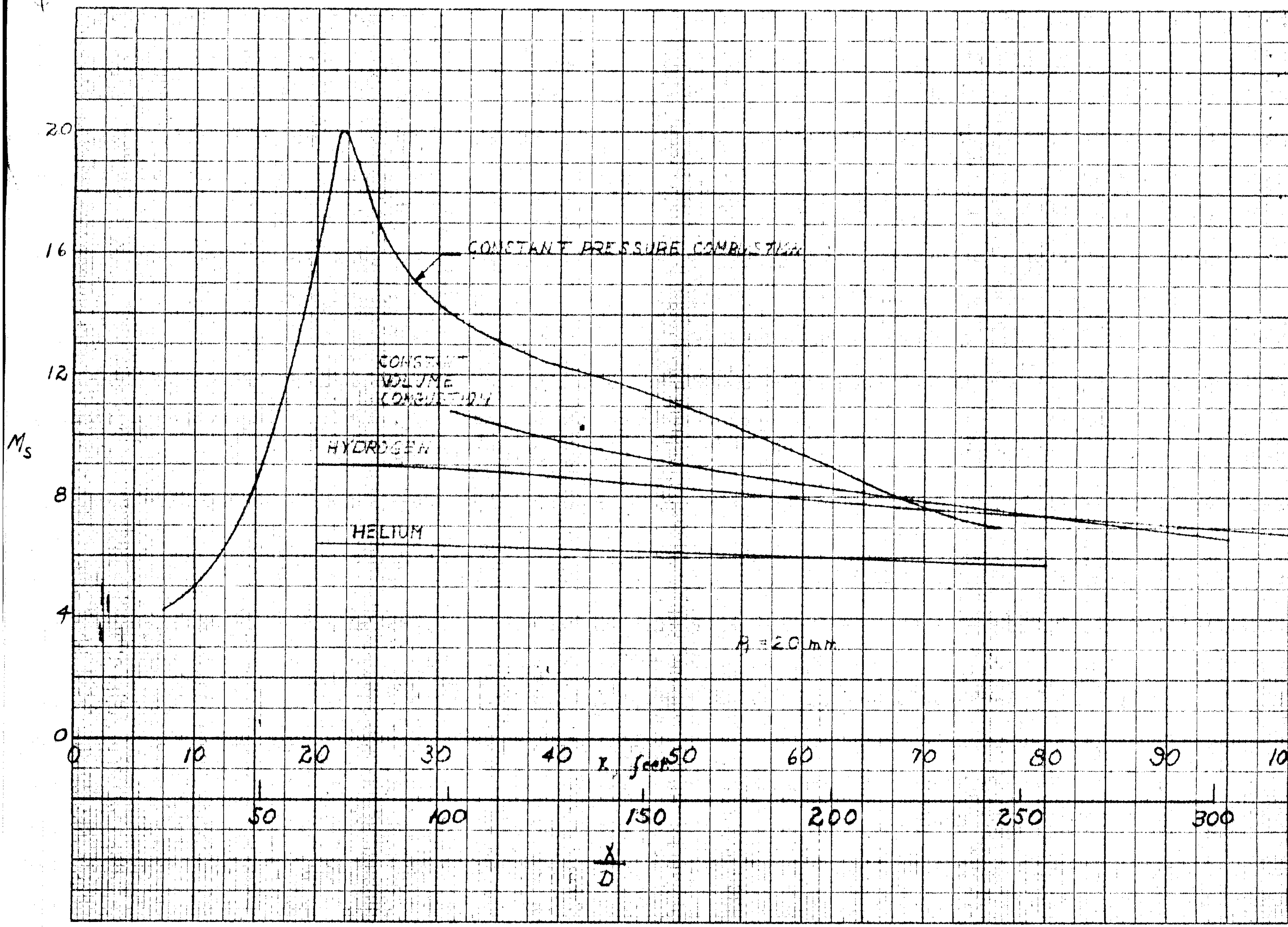
A detailed, systematic investigation of this phenomenon has not been made, but a few tests have brought some interesting results: First, any probe sufficiently insulated from ground (say, a megohm or greater) acquires a charge which may be of the order of a volt or greater when placed in the shock-tube flow and the polarity as well as the actual magnitude of the charge are dependent on the material of the probe. Slide 8 shows examples of the charge on brass and aluminum probes. The reproducibility of the signal for approximately similar running conditions is shown by the two brass probe examples on the slide. Copper and steel probes, as well as brass, show a positive charge in air; aluminum shows a negative charge.

The amplitude of the charge is rather surprisingly insensitive to the temperature level, as shown on slide 9.

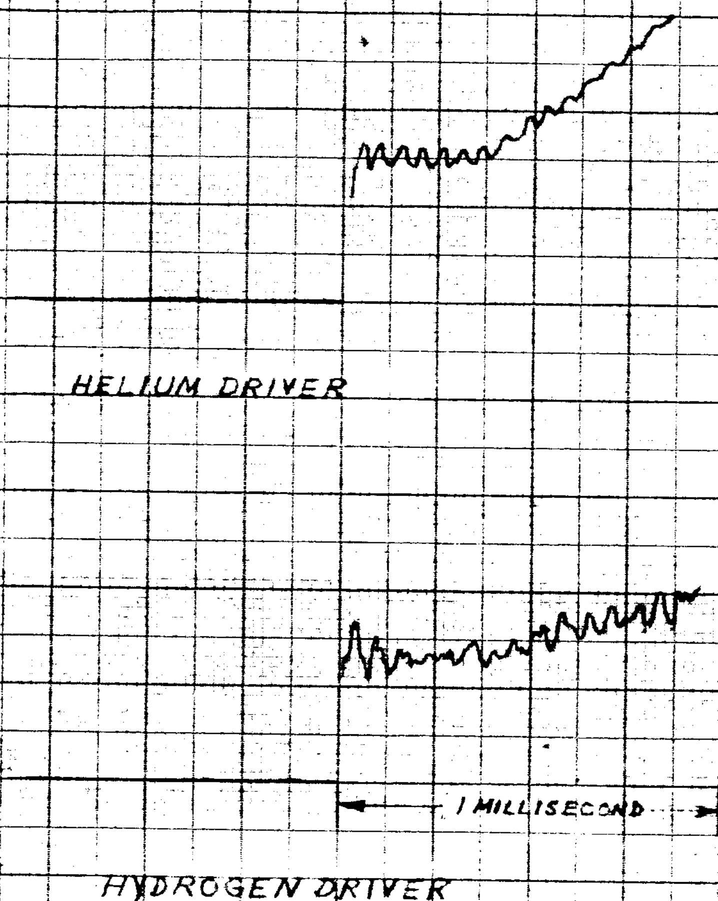
The charge is present when helium is the driven gas and the polarity was negative for all the probe materials tested in helium. Since very little of the helium is ionized at the temperature of this run, it is very possible that impurities are responsible for the presence of the signal here. High velocity of the flow is not necessary, since the charge is very similar for a probe placed at the end of a closed shock tube.

It is not to be expected that a probe will assume the potential of a partially ionized gas in which it is immersed even for the case when the gas is neutral, due to the greater mobility of the electrons. But simple probe theory does not account for the large effect of probe material. The effect of probe material suggests a phenomenon similar to contact electrification. While contact potential difference has been reported for liquids flowing in a pipe, none has been reported between a gas and a metal.

In conclusion, it might be mentioned that present and future work include studies in a small reflected-shock-type nozzle that is now attached to the high-pressure shock tube and somewhat more specific heat-transfer studies.


CONSTANT PRESSURE COMBUSTION
CONSTANT VOLUME COMBUSTION
HYDROGEN
HELIUM
P_1 = 20 mm
M_s
20
16
12
8
4
0
0
10
20
30
40
x, feet
50
60
70
80
90
100
50
100
150
200
250
300
$\frac{X}{D}$

(2)



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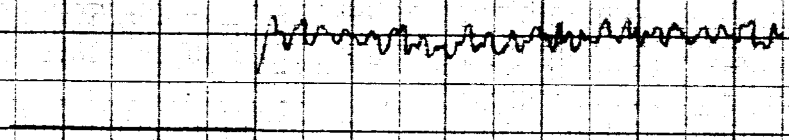
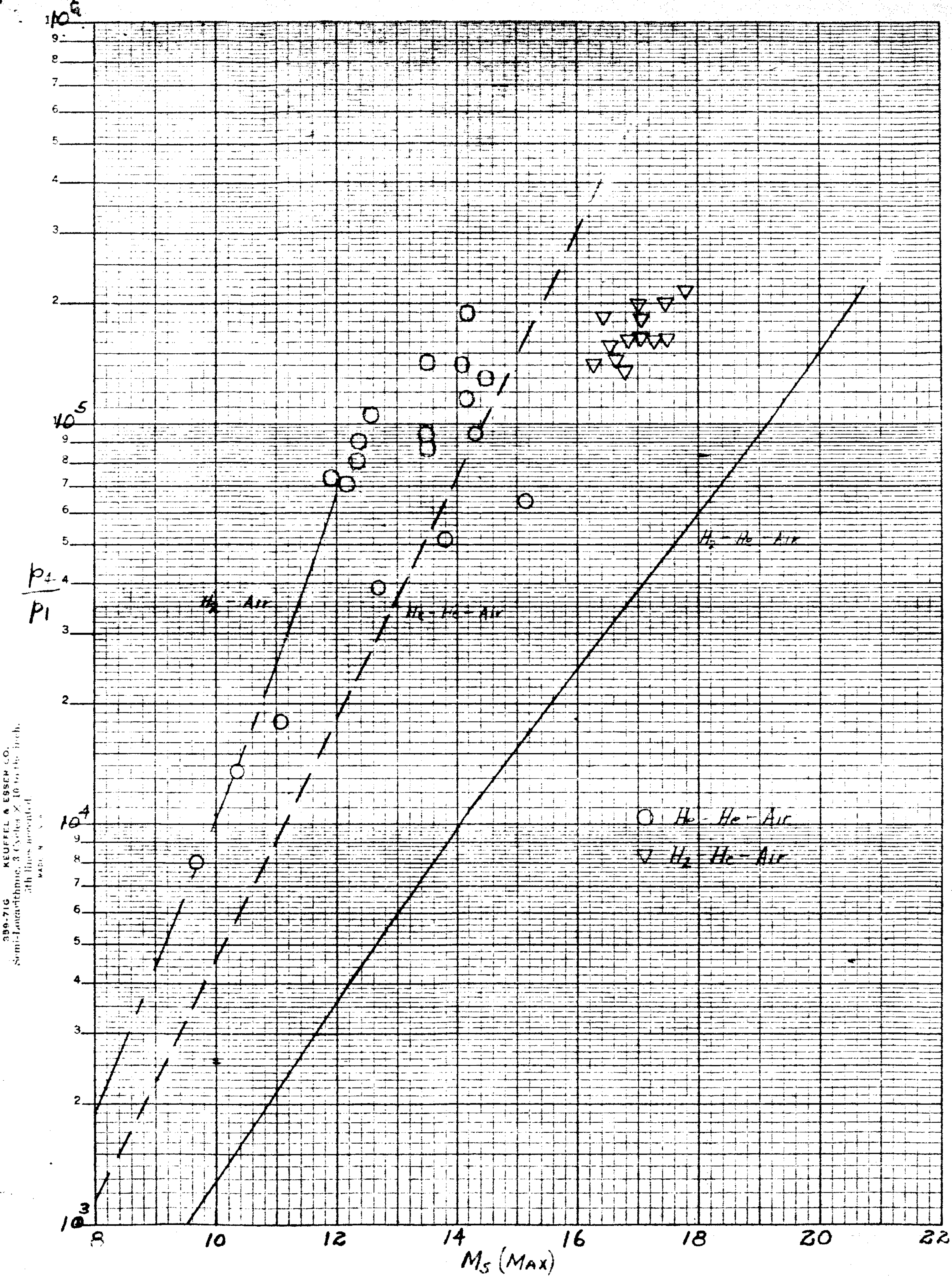


CONSTANT VOLUME COMBUSTION DRIVER

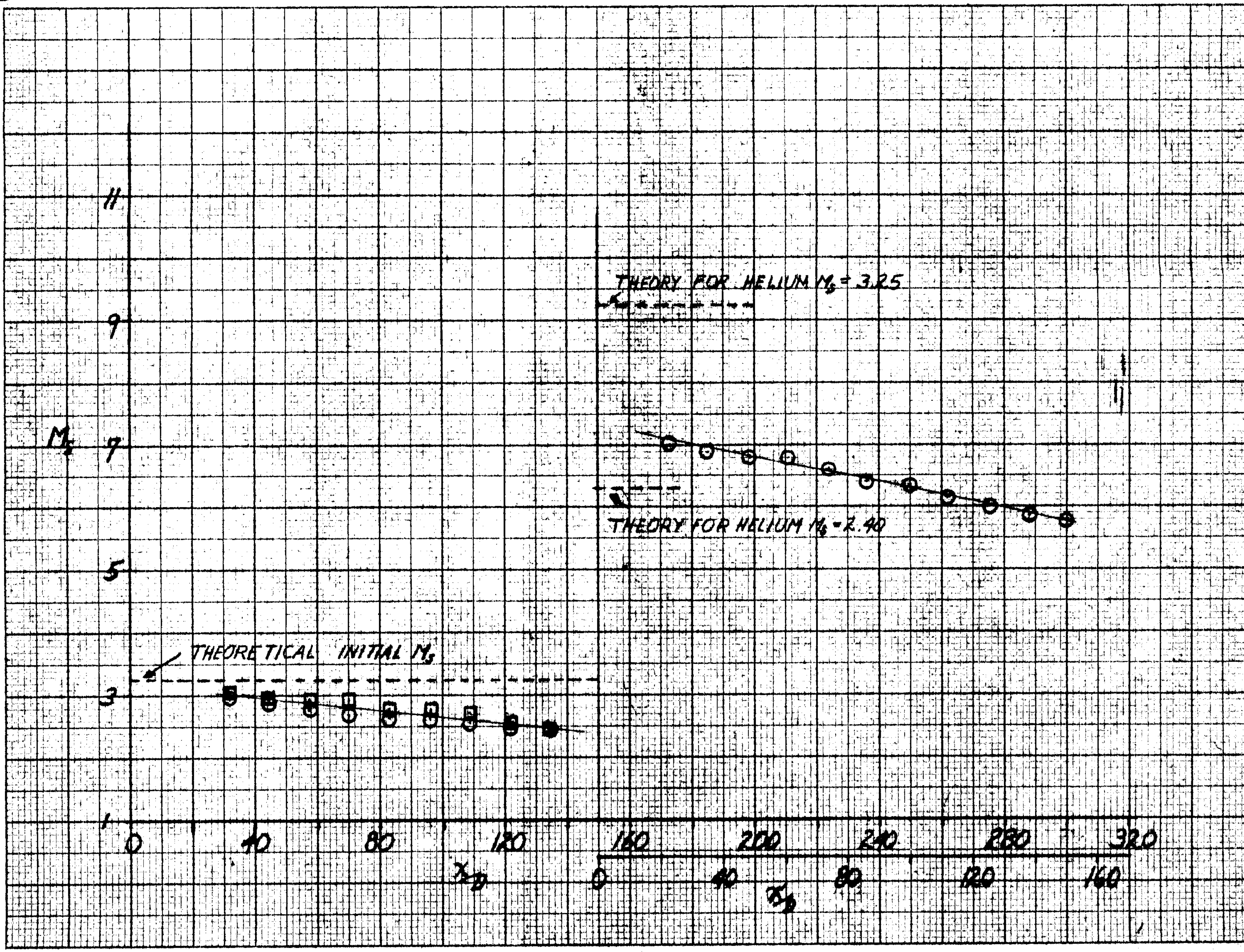
1 MILLISECOND

CONSTANT PRESSURE COMBUSTION DRIVER

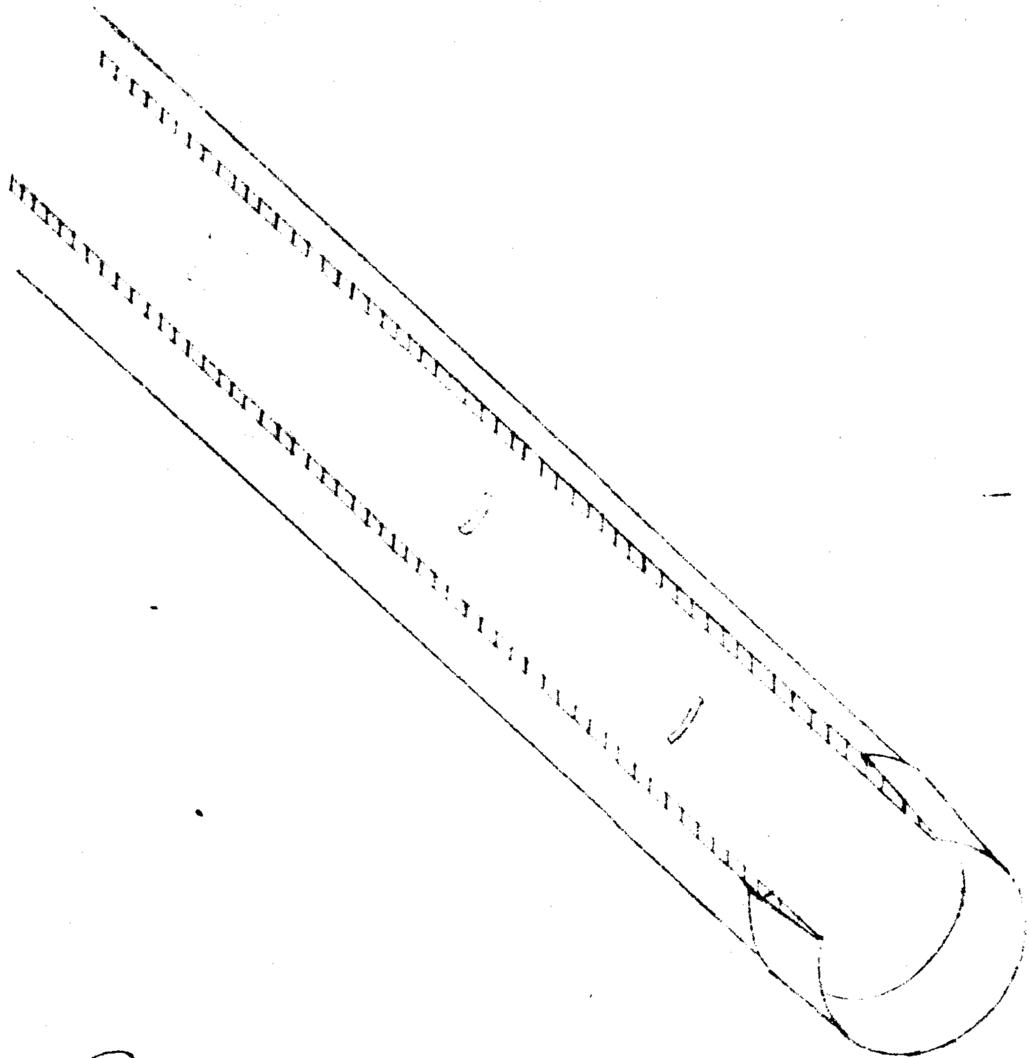
4

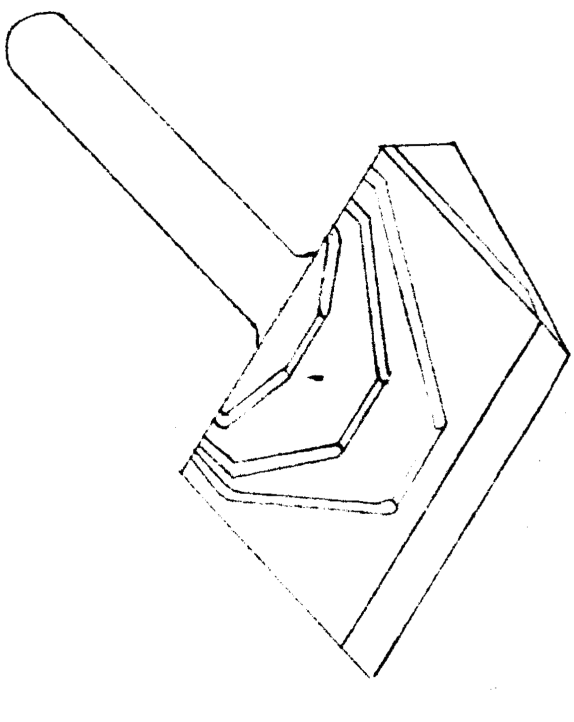

10^6
10^5
10^4
10^3
$\frac{P_4}{P_1}$
H_2 - Air
He - He - Air
H_2 - He - Air
○ He - He - Air
▽ H_2 - He - Air
8
10
12
14
16
18
20
22
M_S (MAX)
359-71G KEUFFEL & ESSER CO.
Semi-Logarithmic, 3 Cycles × 10 to the inch.
5th lines accented.

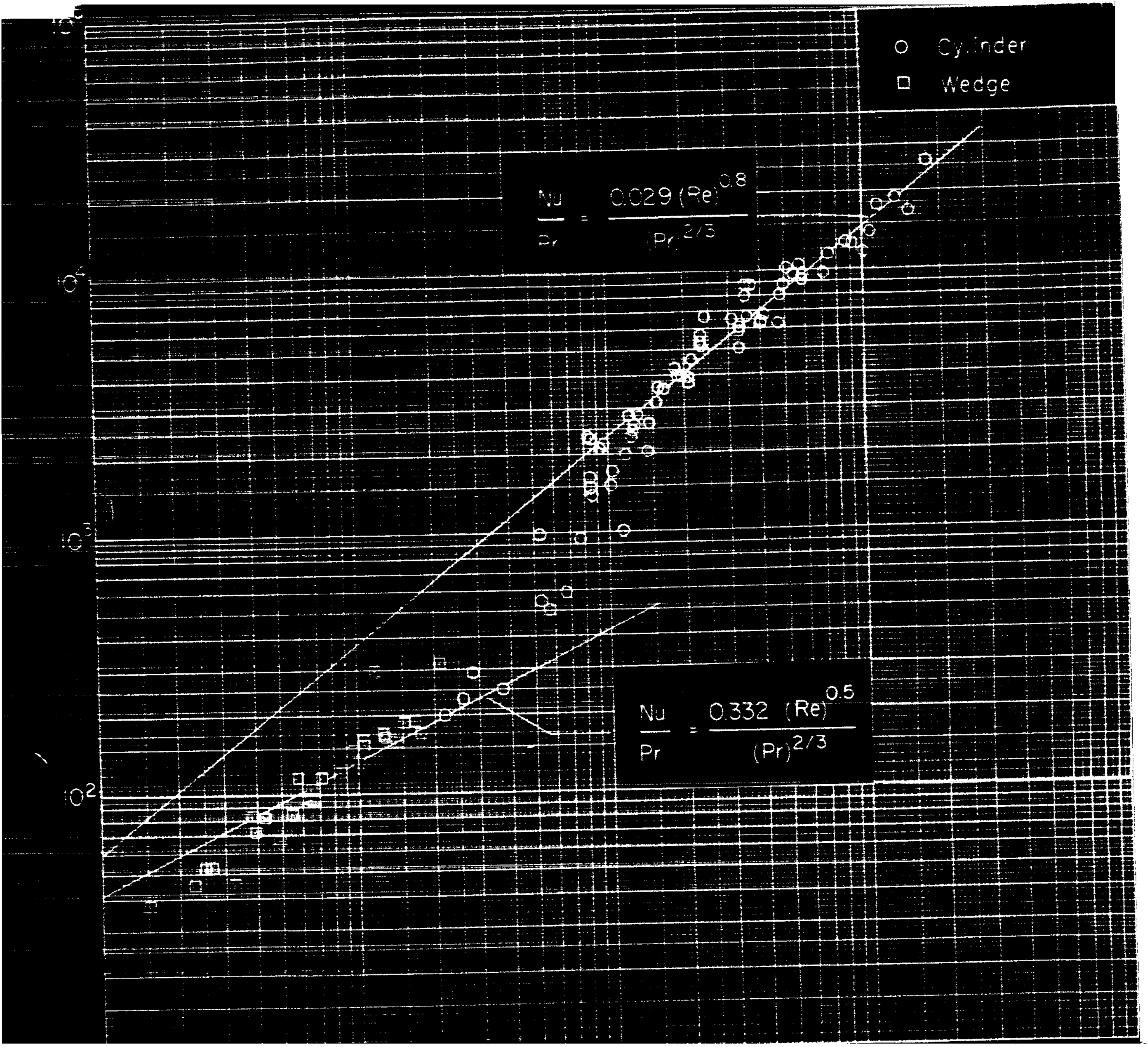
5



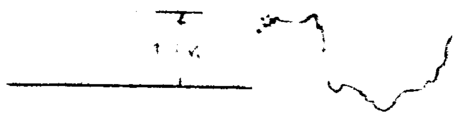
KEUFFEL & ESSER CO. N. Y.



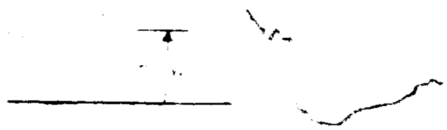




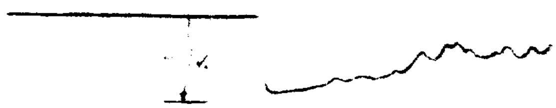
Cylinder
Wedge
$\frac{Nu}{Pr} = \frac{0.029\,(Re)^{0.8}}{(Pr)^{2/3}}$
$\frac{Nu}{Pr} = \frac{0.332\,(Re)^{0.5}}{(Pr)^{2/3}}$
10^4
10^3
10^2



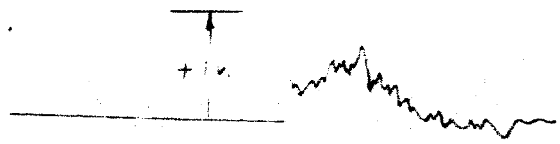
BRASS PROBE



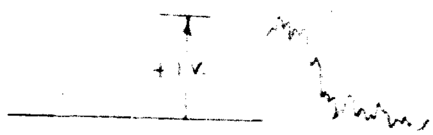
BRASS PROBE



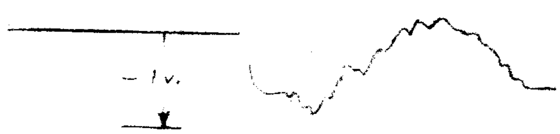
ALUMINUM PROBE



STEEL PROBE IN AIR - T_s = 5900°R



STEEL PROBE IN AIR - T_s = 12,800°R



STEEL PROBE IN HELIUM T_s = 9420°R